

Program in Arms Control, Disarmament, and International Security

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Reprint

**Monitoring Yields
of Underground
Nuclear Tests**

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INTRODUCTION

The United States and the Soviet Union signed the Threshold Test Ban Treaty (TTBT) in 1974 and the Peaceful Nuclear Explosions Treaty (PNET) in 1976. These treaties prohibit underground nuclear explosions having yields greater than 150 kilotons (kt). Although neither party has ratified either treaty, both have separately stated that they will respect the 150 kt limit.

Previously, the Reagan Administration has not sought ratification of these treaties on the grounds that 'we cannot effectively verify Soviet compliance with the 150 kiloton threshold on underground nuclear explosions. The remote seismic techniques we must rely on today to monitor Soviet nuclear tests do not provide yield estimates with the accuracy required for effective verification of compliance.¹ Yield estimates based on teleseismic body wave magnitudes (the method currently used by the U S government) are considered to be uncertain by a factor of two at the 95% confidence level.² This statement means there is one chance in 40 that an explosion with a most likely yield of 150 kt actually had a yield of 300 kt or more. This uncertainty was apparently considered acceptable at the time the TTBT was signed. As discussed later in this report, the best remote seismic methods now available have, according to some experts, an uncertainty of a factor of 1.5 at the 95% confidence level.

Recently, and in accordance with his agreement with the Congress just before the Reykjavik Summit, President Reagan has proposed ratification of the TTBT and PNET with reservations that they not go into effect until the Soviet Union agrees to new monitoring measures to improve verification. The Administration is strongly advocating adoption of the hydrodynamic method of yield estimation, which involves measuring the way in which the shock wave produced by an underground nuclear explosion propagates away from the point of detonation. In particular, the Administration advocates² use of the so called CORRTEX technique for measuring the radius of the shock front as a function of time (CORRTEX is an acronym for *continuous reflectometry for radius versus time experiments*). It believes that it has identified in the hydrodynamic yield estimation method an approach which will reduce the uncertainty in yield measurement to an acceptable level and will do so without danger of compromising other sensitive information about the nature

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or performance of the nuclear device whose yield is to be measured."² The Administration has also stated that the accuracy of the hydrodynamic method is relatively independent of the geologic medium provided only that measurements are made in the strong shock region near the nuclear explosion and expects that the method would provide yield estimates initially accurate to within a factor of 1.3 of the actual yield at the 95% confidence level when applied at Soviet test sites to explosions with yields above 50 kt.² Apparently the Administration considers that an uncertainty of this size is acceptable and hence that the method would provide effective verification of compliance with the TTBT and PNET.

This report summarizes information that is publicly available about the hydrodynamic method of yield estimation and uses this information to consider the strengths and weaknesses of this method for monitoring nuclear test bans.³ Available unclassified data as well as theoretical modeling show that the shock wave produced by an underground nuclear explosion propagates differently in different geologic media. As a result, accurately estimating the yield of an explosion from measurements of the radius of the shock front as a function of time generally speaking requires knowledge of the test geometry and the medium. However the available data and theoretical modeling indicate that there is a relatively brief time during the outward propagation of the shock front when its motion is fairly insensitive to the nature of the medium, for those geologic media which have been studied. If this time is known, if data outside this interval are discarded in making the yield estimate, if the test geometry is known not to be a significant disturbing factor, and if the geologic medium in which the explosion takes place is one for which the U.S. has test data, the available evidence indicates that the yield can be estimated to within a factor of about 1.3 using the hydrodynamic method.

We therefore conclude that the hydrodynamic method could, if used in conjunction with other measurements that determine the nature of the geologic media and exclude possible disturbing factors, provide estimates of the yields of Soviet tests near the 150 kt threshold that are less uncertain than the seismic method currently used by the U.S. government. However, the factor of 1.3 uncertainty expected with the hydrodynamic method is only marginally smaller than the factor of 1.5 uncertainty thought by some experts to be achievable with the best remote seismic methods now available.

A key policy question raised by this study is whether attaching reservations to the TTBT and PNET to permit use of the hydrodynamic method to monitor tests near 150 kt is worthwhile, given possible disadvantages and the modest reduction in the uncertainty of yield estimates that may be expected.

YIELD ESTIMATION METHODS

Phases of a nuclear explosion deep underground —In the following discussion it will be helpful to have in mind what happens when a nuclear charge is detonated deep underground. For present purposes the time development of the explosion may be divided into three phases (see note 4).

- First, the nuclear energy is released in less than a microsecond. This process is accompanied by emission of various types of nuclear radiation. The energy released produces a hot gas bubble in which the pressure and temperature rise steeply, reaching several million atmospheres and about a million degrees within a few microseconds.

- Second the pressure of the hot gases in the bubble initiates a shock wave which moves away from the bubble in all directions at a speed that depends on the yield and is initially greater than the sound speed in the medium. The shock wave compresses the rock through which it travels. At this early time the shock wave is strong enough to completely crush the rock causing it to behave like a fluid. This phase is therefore referred to as the hydrodynamic phase. As the hot gases continue to expand they create a cavity of substantial size, while the shock wave continues to propagate away into the surrounding medium. The hydrodynamic phase ends when the shock wave is no longer strong enough to cause the compressed rock to behave like a fluid.
- Third the shock wave continues to propagate away from the cavity, at first crushing or fracturing much of the rock in the region it traverses but gradually decreasing in strength until it eventually becomes the leading wave of a train of seismic (elastic) waves, which propagate around and through the earth and may be observable thousands of miles away.

Radiochemical method — This method of estimating the yield makes use of the effects of the nuclear radiation emitted during the first phase of the explosion on materials exposed to them. The radiochemical method is the most accurate one but in addition to the yield it can also provide other information about the design and performance of the nuclear device that has been regarded as too sensitive to reveal to the Soviet Union. For this reason it is usually considered inappropriate in the context of treaty verification.⁵

Hydrodynamic method — In the hydrodynamic method of yield estimation the radius of the front of the shock wave is measured as a function of time during the second or hydrodynamic phase. Generally speaking the larger the yield of the explosion the larger the radius reached by the shock front a given time after the detonation. Thus measurements of the radius of the shock front as a function of time when combined with information on the nature and structure of the geologic media in which the explosion occurs and a model of the propagation of the shock wave through these media, may be used to estimate the yield of the explosion.⁶⁻⁹

CORTEX is a particular technique for measuring the radius of the shock front as a function of time.^{10 11} In this technique an electrical cable is lowered into the hole in which the nuclear explosive is placed (the so called *emplacement hole*) or into another hole drilled near the emplacement hole (a so called *satellite hole*). When the expanding shock wave reaches the cable the cable is crushed and electrically shorted. As the shock wave continues to expand the point at which the cable is crushed moves quickly toward the surface. The way in which this point moves is measured by electronic equipment attached to the cable and located above ground. For TTBT verification purposes the Administration is currently proposing placement of the sensing cable in a satellite hole or holes. With accurate knowledge of the location and orientation of the cable with respect to the emplacement hole, measurements of the point at which the cable has been crushed can be converted into estimates of the radius of the shock front as a function of time.

Seismic methods — Seismic methods make use of measurements of ground motions caused by the elastic waves that propagate around and through the earth during the third stage of an underground nuclear explosion described above. Several recent reviews of

these methods exist (see for example refs 12-15) and so they will not be described further here

Discussion —It has been stated several times¹⁶⁻¹⁹ in the context of TTBT and PNET verification that the hydrodynamic method is direct whereas seismic methods are not. From a scientific point of view there is no such distinction. All three methods discussed here involve production of a signal by the exploding device, propagation of that signal to locations more or less remote from the detonation point and detection of the signal by sensors at those locations. Important questions are how the size of the signal varies with yield, how well the propagation of the signal is understood and how accurately and precisely the sensors measure the signal. It has also been implied that use of the hydrodynamic method in and of itself eliminates bias and therefore the need for calibration. It does not. All three methods are subject to both bias and uncertainty. The issue is the actual or potential size of the bias and uncertainty likely to be encountered and whether these are so large as to be of concern. The next section discusses the hydrodynamic method in more detail including possible sources of bias and uncertainty in yield estimates made using this method.

HYDRODYNAMIC METHOD

There are three steps involved in using the hydrodynamic method to estimate yield. They are (1) determine the properties of the geologic media in which the explosion will take place, (2) measure the radius of the shock front as a function of time and (3) estimate the yield of the explosion by fitting a model of the motion of the shock front to the sequence of measurements of the radius of the front.

Measurement of the shock radius —Assuming that the geometry of the CORRTEx cable with respect to the detonation point and the time of detonation can be determined accurately, the CORRTEx equipment can provide a quite accurate measurement of the radius of the shock front as a function of time. Determining the geometry requires an accurate survey of both the hole in which the CORRTEx cable is to be inserted and the hole in which the nuclear device is to be placed. The time of detonation is determined from the time of arrival of the electromagnetic pulse (EMP).²⁰ During a typical test the CORRTEx equipment records the radius of the shock front at several thousand times.¹⁰

Modeling the motion of the shock front —In order to derive a yield estimate from the radius of the shock front as a function of time, one must have a model of the propagation of the shock wave away from the detonation point. This propagation has been modeled in several ways. These include

- Use of one- and two-dimensional hydrodynamic computer codes which numerically solve the fundamental conservation equations together with constitutive relations that describe the response of the geologic media to applied stresses.^{21, 22}
- Use of one-dimensional similarity solutions that incorporate the equation of state of the geologic medium.^{3, 7-9}
- Use of an empirical power law formula whose parameters are estimated by fits to U.S. test experience.^{6-9, 21}

No details were available to the author about the two-dimensional hydrodynamic computer codes and equations of state used to model ground shock propagation at Los Alamos²¹ at the closing date for this report. Nor are any unclassified CORRTEX data currently available. Consequently the theoretical models described here are similarity solutions³ based on published equations of state^{7,9,23} while the test data mentioned are radius versus time measurements made using the so-called SLIFER method²⁴ a shock radius measurement technique that was used prior to the CORRTEX technique.

Similarity solutions and SLIFER data—The solutions discussed here make the following key assumptions: (1) the explosion is spherically symmetric; (2) the medium between the center of the explosion and the measuring cable or cables is homogeneous; (3) the shock wave is strong enough to crush the material through which it is propagating sufficiently to cause it to behave like a fluid; (4) the properties of the shocked medium are adequately described by a Hugoniot equation of the form $D = a + bU$, where D and U are the shock and particle velocities, respectively, and a and b are constants; and (5) the similarity assumption that the specific energy of the material just behind the shock front is a constant fraction of the mean specific energy of the material within the shocked region.²⁵ The Rankine-Hugoniot jump conditions across the shock front are of course satisfied. Despite their simplicity, these solutions agree well with the available SLIFER data, particularly if the phase changes that occur in some media at pressures below about 1 million times atmospheric pressure are taken into account.^{3,7-9}

At early times, the shock wave is strong and the similarity solution is a self-similar blast wave.^{3,7,8} During this phase the radius of the shock front depends on the density and equation of state of the medium and on the yield of the explosion. No unclassified test data on this phase are available. At moderately late times, the similarity solutions predict that the shock wave will propagate as a self-similar compressional wave in the (crushed and fluidized) medium. During this latter phase the motion of the shock front depends only on the so-called plastic wave speed²⁶ in the medium. Over a broad range of intermediate times, the similarity solutions are neither blast waves nor plastic waves. During this intermediate period the shock wave is only moderately strong, in the sense that the shock velocity is only a few times greater than the plastic wave speed, and hence the radius of the shock front depends not only on the density and equation of state of the medium and the yield, but also on the plastic wave speed in the medium. The similarity solutions appear to give a good description of SLIFER data, which are available at intermediate and moderately late times during the hydrodynamic phase.^{3,7-9}

The similarity solutions and SLIFER data indicate that the shock wave produced by an explosion of given yield generally develops differently in different media. This is not surprising, since the density and plastic wave speed, for example, vary by factors of 1.6 and 3, respectively, for geologic media for which test data are publicly available.^{7,8} As a result, the characteristic radius R where the shock wave produced by a 150 kt explosion changes from a blast wave to a plastic wave varies from about 100 feet in wet tuff to over 200 feet in dry alluvium. In basalt and granite, R is about 120–130 feet for this yield. Therefore, a yield estimate made by fitting a model of shock propagation to radius versus time measurements over a broad interval will generally be biased by any errors in the assumed properties of the medium. Similarly, unanticipated variations in the properties of a given type of rock, such as granite, within the deposit in which the explosion is detonated will introduce uncertainty in such a yield estimate.

However for the geologic media for which test data are available (the dry alluvium partially saturated tuff, saturated tuff granite, basalt, and rhyolite at the test sites used) the density equation of state, and plastic wave speed are correlated in such a way that there is a comparatively brief interval during the transition from blast wave to plastic wave when the radius of the shock front is relatively insensitive to the medium but relatively sensitive to the yield.^{3,23} At present, this correlation does not appear to be well understood from any fundamental physical point of view. The time at which this insensitive interval occurs depends on the yield W of the explosion as $W^{1/3}$, varying from about 0.2 milliseconds after a 1 kt explosion to about 1 millisecond after a 150 kt explosion. Almost all of the test data on which this conclusion is based come from nuclear explosions at the Nevada Test Site. This conclusion is also reportedly supported by modeling.²² If there are other relevant media whose properties are *not* correlated in this way the insensitive interval does not exist. Thus insensitivity to the medium can only be assured for materials that have been tested.

Los Alamos algorithm —The algorithm used at Los Alamos to derive yields is to fit a power law equation (the so called Los Alamos formula) to CORRTEx data.^{6-9,21} The formula is fit over the time interval from 0.1 to 0.6 milliseconds after detonation for an explosion with a yield of 1 kt or 0.5 to 3.2 milliseconds for an explosion with a yield of 150 kt. These time intervals correspond to distances ranging from 6 to 16 feet from the detonation point for an explosion with a yield of 1 kt or from 35 to 85 feet for an explosion with a yield of 150 kt. (Both times and distances are assumed to scale with W as $W^{1/3}$.) They lie within the interval of insensitivity for media so far tested.³ Over this interval, the Los Alamos formula as quoted in the literature⁷⁻⁹ agrees with both the similarity solution and available SLIFER data to within a factor of about 2 (the published formula may not reflect current practice).

The Los Alamos formula is an empirical relation, *i.e.*, it is not derived from fundamental physical principles but is instead obtained by fitting a simple power law expression to a collection of shock wave data. The formula must therefore be regarded as established only for those geologic media and pressure regimes where it has actually been verified. At distances less than the stated lower limit of validity practical operational and engineering considerations make accurate measurements difficult. At still smaller distances the formula disagrees with the similarity solution. At distances greater than the stated upper limit of validity, the Los Alamos formula departs from the similarity solution and SLIFER data. At these distances the radius of the shock front is no longer insensitive to the medium.

In order to use the Los Alamos algorithm the cable must sample the insensitive interval. In order to do this the cable must extend to within about 35 feet of the detonation point for a 150 kt explosion or within 6 feet for a 1 kt explosion. Most of the data accumulated by the CORRTEx equipment are not within the insensitive interval. The shortest pulse interval possible with current CORRTEx equipment is 10 microseconds.¹⁰ Thus of the 2,000 or so radius measurements made during an explosion all but about 40 must be discarded for an explosion with a yield of 1 kt and all but about 200 for an explosion with a yield of 150 kt, in order to keep only data within the stated range of validity of the Los Alamos algorithm. Data from outside this range can of course provide additional information on the yield and a check on the consistency of the algorithm if there is adequate knowledge of the geologic medium.

According to official statements^{1 2} the Los Alamos algorithm gives yields accurate to within a factor of 1 15 (at the 95% confidence level) of the yields given by the more accurate radiochemical method, for explosions with yields greater than 50 kt conducted at the Nevada Test Site. According to these same statements, the formula is expected to be accurate to within a factor of 1 3 at Soviet test sites. These statements are consistent with the results of the present study provided that only data from within the region of insensitivity are used in the analysis that the media in which Soviet tests take place are within U S experience that possible effects which could interfere with CORRTEx measurements can be excluded and that test geometries which would significantly disturb the shock wave from a spherically symmetric wave can be recognized and allowed for.

Factors affecting hydrodynamic yield estimates —From the preceding discussion it is apparent that yield estimates made using the hydrodynamic method may be affected by a number of factors related to the geology of the test site and the geometry of the test. Factors that may introduce bias or increase uncertainty include⁶

- Any errors in the survey used to establish the path of the CORRTEx cable relative to the emplacement hole if the CORRTEx cable is placed in a satellite hole
- Any properties of the nuclear device emplacement configuration or surrounding geologic media that cause the shock wave to propagate faster in one direction than another. The size of these effects is less for high-yield than for low yield explosions
- Emplacement of cables or other aspects of the test setup that cause other signals to interfere with measurement of the ground shock radius as a function of time
- Any errors made in discarding data that are disturbed or are outside the insensitive interval and any errors in applying corrections to the data

Although over 100 tests have been carried out with the CORRTEx sensing cable in the emplacement hole, experience using current CORRTEx equipment with the cable placed down a satellite hole is apparently limited (according to official statements, only four tests with this geometry have been carried out²). SLIFER data from satellite holes are available for several tens of earlier explosions²²

Possible requirements for establishing confidence in the precision of hydrodynamic yield estimates made at Soviet test sites —Clearly the more information that is available about the explosion and the nature of the geologic media in which it occurs and the more restrictions there are on the test geometry the more accurate the hydrodynamic method will be. Some idea of the information that may be required to obtain uncertainties of a factor of 1 15 to 1 3 is provided by the Protocol to the PNET which explicitly established the use of the hydrodynamic method as one of the monitoring methods that could be used for any explosion with a planned aggregate yield exceeding 150 kt. At the time the PNET was signed the following information about the geologic medium was specified in the Treaty Protocol as needed to adequately verify the Treaty²⁷

- The type or types of rock and their physical properties including density seismic velocity, porosity degree of liquid saturation, and rock strength

- Specific features of the geologic structure that could affect the yield estimation
- The length of the cannister containing the nuclear charge [and possibly containing diagnostic equipment, in the case of a weapon test] the dimensions of the tube or other device used to emplace the cannister, the cross-sectional dimensions of the emplacement hole, the nature of the materials (including their densities) used to fill the emplacement hole
- The configuration of any known voids with a volume greater than one cubic meter within the area

Measures specified to obtain this information included

- Examination of rock core or rock fragments removed from the emplacement hole, and of any logs or drill core from existing exploratory holes
- A choice of one of several alternatives that include observation of construction of the emplacement hole removal and examination of rock core or rock fragments from the wall of an existing exploratory hole, removal and examination of rock core or rock fragments from the wall of the emplacement hole and construction of one or more new exploratory holes
- Observation of the emplacement of the explosive and confirmation of the depth of emplacement
- Observation of the stemming of the emplacement hole
- Continuous unobstructed visual observation of the area of the entrance to the emplacement hole
- Photography of the exterior of facilities and installations associated with the conduct of the explosion

In addition, the Protocol placed specific limits on the dimensions of the cannister and required that tubes and conduits emerging from the emplacement point be filled with material of a density greater than a specified value. These measures were motivated by the requirement that the sensing cables be placed in the nuclear device emplacement hole. To ease many of the restrictive requirements of the PNET Protocol it has been proposed that CORRTX cables be placed in satellite holes for verification of weapon tests.

In order to provide assurance that the yield estimates derived from CORRTX measurements are accurate for weapon tests and peaceful nuclear explosions near the 150 kt limit, Protocols specifying measures like these would be required.^{28,29}

Relative intrusiveness —The CORRTX method is more intrusive than remote seismic methods for the following reasons

- Personnel from the other country must be present at the test site before and during the test and therefore have an extensive opportunity to observe test preparations. This would pose operational security problems.³⁰
- Achievement of an uncertainty of a factor of 1.3 or less requires examination of the contents of the bore hole down which the CORRTX cable is placed, and may require additional measurements and some constraints on test configurations (see above)

- The canister containing the nuclear device and any diagnostic equipment must be examined to verify that the conditions necessary for the yield estimate to be valid are satisfied. For tests of nuclear directed energy weapons, this examination could reveal sensitive design information unless special procedures are followed.³⁰
- Achievement of confidence in the estimated yield may, for some test geometries, require placement of several sensing cables around the weapon emplacement point.
- Unless precautions are taken, the CORRTEx sensing cable and equipment could be affected by the electromagnetic pulse (EMP) generated by the explosion. Such precautions might be considered a hindrance in carrying out some tests. A detailed analysis of the EMP could reveal sensitive information about the design and performance of the nuclear device being tested. Therefore the electrical equipment used for yield estimation must be designed so that it does not acquire detailed EMP signatures.

Placing the sensing cable down the emplacement hole is relatively intrusive in weapon tests since in this location it is more likely to collect sensitive information that could reveal the nature of the test. This problem would be alleviated if the sensing cable is placed in a satellite hole, as proposed for TTBT monitoring.

Use of the CORRTEx method to monitor low threshold or comprehensive test bans —A question that has arisen repeatedly in discussions of CORRTEx is whether the method can be used at yields lower than 50 kt. Underground nuclear explosions as small as 1 kt produce shock waves that evolve in the same way as those produced by explosions of larger yield. At such yields some engineering and operational problems are likely to be more difficult. For example, drilling a satellite hole within 6 feet of the emplacement hole to the depths of typical nuclear device emplacement as would be required for use of CORRTEx to measure the yield of a 1 kt explosion appears challenging. The need for such close placement would place restrictions on the size of the canisters used to contain the diagnostic instrumentation. Use of small canisters with diagnostic lines-of sight to the detonation point could disturb the CORRTEx measurements although placing the CORRTEx cable in a satellite hole should lessen such disturbances. Because the radii to be measured are much smaller, any survey errors become more important. Apparently the feasibility and desirability of using CORRTEx for monitoring a low threshold test ban treaty have not yet been carefully studied.

The CORRTEx method is not suited for detecting unannounced nuclear tests because it requires activity at the site in advance and the presence of monitoring personnel during the test. Because it is only sensitive to nuclear explosions that are very nearby, the method is also not suitable for monitoring a comprehensive test ban.

Comparison with remote seismic methods —It may be helpful to compare the expected uncertainty of yield estimates made using CORRTEx with the expected uncertainty of yield estimates made using remote seismic methods. As mentioned in the Introduction, yield estimates based on seismic body wave magnitudes (the method currently used by the U.S. government) are considered to be uncertain by a factor of two at the 95% confidence level.²

However, at least two other remote seismic methods are available: a method based on measurement of surface waves and the so-called Lg method, which uses a wave guided in

the continental crust. If both these additional methods are assumed to provide independent yield estimates that are, like those derived using the body wave method, uncertain by a factor of two at the 95% confidence level, yield estimates obtained by combining all three remote seismic methods would be uncertain by a factor of 1.5 at the 95% confidence level.^{31 32} (The actual uncertainty could well turn out to be less than this, since the uncertainty of yields estimated using the Lg method alone has been reported as a factor of 1.3 at the 95% confidence level when the method is used for explosions with yields near 150 kt.³³)

This uncertainty of a factor of 1.5 expected by some experts is only marginally larger than the uncertainty of a factor of 1.3 which the Administration expects from use of the CORRTEx method. Some experts think that the surface wave and Lg methods could significantly reduce the uncertainty of seismic yield estimates even if measurements are made only outside the Soviet Union (some of these measurements would be at so called teleseismic distances of thousands of miles whereas others could be at so called regional distances). At large distances, uncertainties in the attenuation of Lg waves become more important. For this reason, measurements at regional distances would be advantageous. If many stations at regional distances are thought necessary, this would require modification of the TTBT and PNET.

CONCLUSIONS

In the present report we have reviewed information that is publicly available about hydrodynamic yield estimation methods and CORRTEx measuring equipment, and have considered the strengths and weaknesses of this approach for monitoring nuclear test bans. Our key conclusions are as follows:

- The hydrodynamic method and CORRTEx equipment could, if used in conjunction with other measurements and some restrictions on test designs, provide estimates of the yields of Soviet tests near the 150 kt threshold with an uncertainty of about a factor of 1.3 for test media within U.S. experience.
- The feasibility of using the hydrodynamic method and CORRTEx to monitor a threshold test ban treaty with a threshold substantially less than 150 kt has not yet been studied carefully. There are engineering and operational difficulties that may be expected in using the method to monitor a low threshold test ban and that need to be examined in a verification context.
- The hydrodynamic method is not suited for detecting unannounced nuclear tests or for monitoring a comprehensive test ban agreement.
- The uncertainty of a factor of 1.3 at the 95% confidence level expected for the hydrodynamic method and CORRTEx is only marginally smaller than that thought to be achievable with the best remote seismic methods now available, which according to some experts are expected to have an uncertainty of a factor of 1.5 or less at this same confidence level.

A key policy question raised by this study is whether attaching reservations to the TTBT and PNET to permit use of the hydrodynamic method to monitor tests near 150 kt is worthwhile, given possible disadvantages and the modest reduction in the uncertainty of yield estimates that may be expected.

It is a pleasure to thank G S Miller for help in computing similarity solutions and for numerous helpful discussions of yield estimation using the hydrodynamic method

NOTES

- 1 *U S Policy Regarding Limitations on Nuclear Testing* (U S Department of State Special Report No 150 August, 1986)
- 2 *Verifying Nuclear Testing Limitations Possible U S -Soviet Cooperation* (U S Department of State Special Report No 152 August 14 1986)
- 3 A more detailed technical report is in preparation
- 4 S Glasstone and P J Dolan *The Effects of Nuclear Weapons* (U S Government Printing Office Washington D C 1977) pp 61 62 and 238
- 5 W K H Panofsky testimony before the Senate Committee on Foreign Relations January 15 1987
- 6 J T Rambo *Rep UCID-17292* (Lawrence Livermore National Laboratory Livermore California, 1976)
- 7 M Heusinkveld *Rep UCRL 52648* (Lawrence Livermore National Laboratory Livermore California 1979)
- 8 M Heusinkveld *J Geophys Res* 87 1891 (1982)
- 9 M Heusinkveld *Mem 0004A* (Earth Sciences Department Lawrence Livermore National Laboratory Livermore California October 30 1986)
- 10 C F Virchow G E Conrad D M Holt and E K Hodson *Rev Sci Instrum* 51 642 (1980)
- 11 Los Alamos National Laboratory public information sheet on CORRTEX (April 1986)
- 12 L R Sykes J F Evernden and I Cifuentes in *Physics Technology and the Nuclear Arms Race AIP Conf Proc No 104* (American Institute of Physics New York 1983)
- 13 W J Hannon *Science* 227 251 (1985)
- 14 J F Evernden and C B Archambeau in *Arms Control Verification* (Pergamon Brassey s New York 1986)
- 15 J F Evernden C B Archambeau and E Cranswick *Revs Geophys* 24 143 (1986)
- 16 H A Holmes testimony before the Senate Committee on Foreign Relations January 13 1987
- 17 J H McNally testimony before the Senate Committee on Foreign Relations January 13 1987
- 18 R B Barker testimony before the Senate Committee on Foreign Relations January 13 1987
- 19 D A Vesser testimony before the Senate Committee on Foreign Relations January 13 1987
- 20 R A Jefferies private communication
- 21 D D Eilers *Mem P 15-87 U 37* (Los Alamos National Laboratory January 28 1987)
- 22 R E Hill *Mem P 15-87 U-69* (Los Alamos National Laboratory February 10 1987) According to this memorandum the two-dimensional code used is the code SOIL available commercially from Computer Code Consultants Inc 400 10th Avenue NW Chisholm MN 55719 The formulation of this code has reportedly been described in W E Johnson *TOIL (A Two Material Version of the OIL Code)* (General Atomic Report GAMD 8073 1967) W E Johnson *Code Correlation Study* (Air Force Weapons Laboratory Report AFWL TR 70 144 April 1971) and *Dynamic Response of Materials to Intense Impulse Loading* (P C Chou and A K Hopkins eds Air Force Materials Laboratory 1977)
- 23 W R Perret and R C Bass *Rep SAND 74 0252* (Sandia Corp Albuquerque New Mexico 1975)
- 24 M Heusinkveld and F Holzer *Rev Sci Instrum* 35 1105 (1964)
- 25 These solutions are not fully self similar In a fully self similar shock wave the distributions with radius of the flow variables such as the pressure and density, evolve with time in such a way that only their scales and the radius of the shock front change while the shape of the distributions remains unaltered (see L I Sedov *Similarity and Dimensional Methods in Mechanics* (Academic Press New York 1959 [English Translation]) For such motions assumption (5) is automatically satisfied Moreover all the scales have a power law (or occasionally exponential) dependence on time As discussed below the solutions referred to here are fully self similar only early when they are blast waves and at late times when they are plastic waves Furthermore the fraction referred to in assumption (5) is expected to be different for the early and late motions and hence not constant. Thus for the solutions discussed here assumption (5) must be regarded as an approximation

- 26 See Ya B Zeldovich and Yu P Raizer *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena* (Academic Press New York 1967 [English Translation])
- 27 *Arms Control and Disarmament Agreements* (U S Arms Control and Disarmament Agency Washington D C 1982)
- 28 S S Hecker testimony before the Senate Committee on Foreign Relations January 15 1987
- 29 M D Nurdyke testimony before the Senate Committee on Foreign Relations January 15 1987
- 30 R E Batzel testimony before the Senate Committee on Foreign Relations January 15 1987
- 31 R Alewein as quoted in the Minutes of the November 4 5 1985 meeting of the Committee on Seismology of the National Research Council Board on Earth Sciences
- 32 P G Richards testimony before the Senate Committee on Foreign Relations January 15 1987
- 33 O W Nuttli *J Geophys Res* 91 2137 (1986)